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Upgrade of SULTAN/EDIPO for HTS cable test

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Abstract

CRPP hosts two unique conductor test facilities SULTAN (SUpraLeiter TestANlage) and EDIPO (European DIPOle). They allow the test of high current superconductors in high magnetic fields (SULTAN 11 T, EDIPO 12.5 T). In both facilities sample currents up to 100 kA can be supplied by means of a NbTi transformer. Presently the facilities are upgraded for the test of high current high-temperature superconductor (HTS) samples. For HTS conductor testing at temperatures between 20 and 50 K, the heat flux between the HTS sample under test and the NbTi transformer needs to be limited to around 10 W per conductor leg by means of an HTS adapter connecting them. The second required upgrade is the supply of intermediate temperature helium (20-50 K) to the HTS test conductor. It is mandatory that the helium gas coming from the HTS conductor under test can be returned to the cryoplant as cold gas (T < 20 K). To reach this goal a tube-in-tube heat exchanger has been manufactured in which 4.5 K helium coming from the cryoplant is in counter flow with the warm gas leaving the HTS test conductor.

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Keywords: HTS high current cables; test of HTS high current cables, coated conductors, test facilities, tube-in-tube heat exchanger

1. Introduction

In the last few years, the performance of RE-123 coated conductors of long length increased substantially. The fusion community has started to consider the option that high-T_c superconductors may be used in a longer term in the large superconducting magnets of future fusion reactors.

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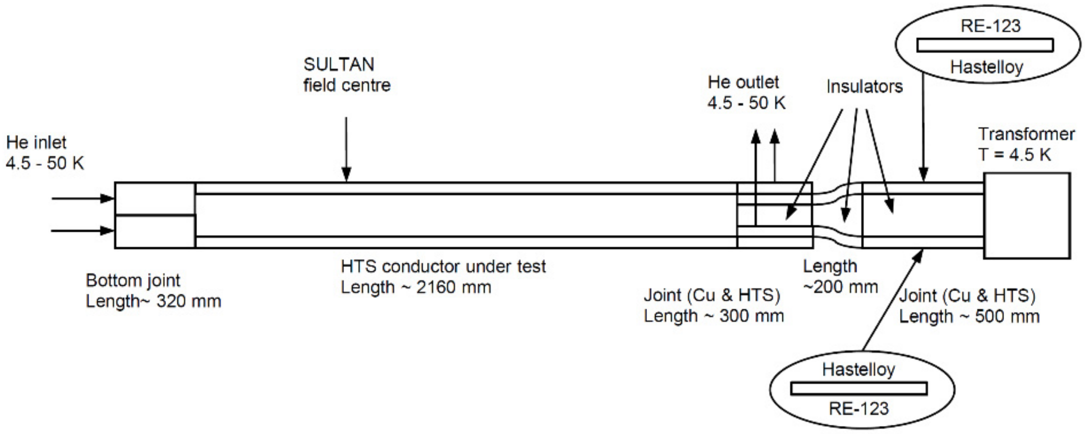

Fig. 1. Sketch of a SULTAN HTS sample consisting of two conductor legs.

For the manufacture of high current conductors using thin coated conductor tapes of high aspect ratio, the cable concepts of a twisted stacked-tape cable (TSTC) (Takayasu et al. [1]), a conductor on round core cable (CORC) (Van der Laan et al. [2]) and of a coated conductor Rutherford cable (CCRC) (S.I. Schlachter et al. [3]) have been developed. At CRPP a 50 kA class flat cable, composed of RE-123 twisted stack super-strands, is presently manufactured (Uglietti et al. [4]). Due to these cable developments there will be soon a demand for the test of high current HTS conductors at elevated temperatures in high magnetic fields. The present upgrade of the CRPP test facilities will make available such testing opportunities by the end of the year 2014.

A sketch of an HTS SULTAN sample is presented in Fig. 1. The total length of the HTS conductor sample is ≈2780 mm including the joints at both ends. The two legs of the HTS adapter need to be bent in such a way that the RE-123 side of the tapes points towards the copper shoes of the NbTi transformer and towards the HTS sample under test. The present article focuses on the manufacture of the HTS adapter and the heat exchanger required for the upgrade of SULTAN or EDIPO for the test of high current HTS conductor samples at temperatures between 20 and 50 K. The HTS adapter and the heat exchanger are suitable to be used in SULTAN or EDIPO.

2. HTS adapter design

An outline design of the HTS adapter was already presented in a previous paper by Wesche et al. [5]. As compared to this initial design the arrangement of the RE-123 coated conductor tapes was changed in such a way that the broad face of the tapes is now parallel to the stray field (see Fig. 2). In each of the two legs of the HTS adapter, the current is carried by 5 stacks of RE-123 tapes of 12 mm width. Each stack is composed of 15 RE-123 tapes with a minimum critical current of 300 A at 77 K and self-field. The main properties of the superconductor tapes supplied by SuperPower™ are listed in Table 1. The expected stray field at the position of the warm end of the HTS adapter is 0.35 T in SULTAN and 0.19 T in EDIPO. Because of the small distance between the RE-123 stacks at the warm ends of the two legs of the HTS adapter the magnetic field is dominated by the self-field contribution at high sample currents of 100 kA. The expected current carrying capacity of the HTS adapters is 100 kA at 40 K.

Table 1. Properties of the SCS12050-AP RE-123 coated conductors supplied by SuperPower™.

Parameter	Value	Parameter	Value
Tape width (mm)	12	Thickness of Hastelloy™ substrate (μm)	50
Tape thickness (μm)	71	Total length (m)	105
Thickness of RE-123 film (μm)	≈1	Minimum I_c at 77 K, sf (A)	327
Thickness of Ag layer (μm)	2	Reduced copper stabilizer thickness (μm)	16 (8 on each side)

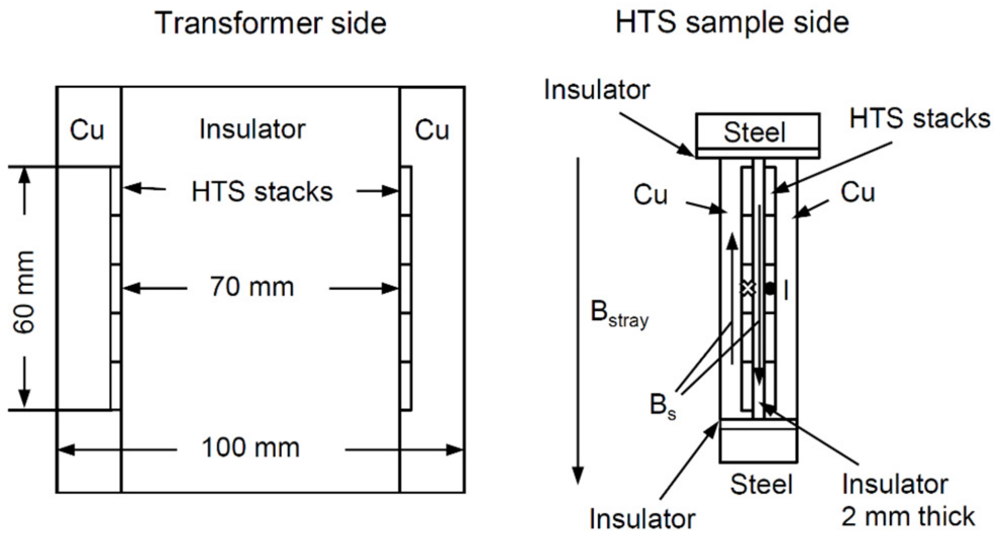

Fig. 2. Sketch of the cross-section of the HTS adapter at the transformer and the sample side.

The main design parameters of the HTS adapters are gathered in Table 2. The heat flux between the NbTi transformer at 4.5 K and the warm end of the HTS adapter has been estimated from the integrated thermal conductivity of copper with *RRR* = 60 (58360 W/m), silver with *RRR* = 190 (≈88000 W/m) and Hastelloy™ (232 W/m) and their cross-sections. The contributions of RE-123, the buffer layers and stainless steel have been neglected.

Table 2. Main design parameters of the HTS adapter.

Parameter	Value
Number of RE-123 stacks per leg	5
Number of RE-123 tapes per stack	15
Total number of tapes per leg	75
Nominal length (mm)	200
Temperature at cold/warm end (K)	4.5/50
Estimated heat flux per leg (W)	≈5

3. Manufacture of the HTS adapters

First the RE-123 tapes of 12 mm width were pre-tinned with Pb-Sn solder. For the soldering of the RE-123 tapes to the copper end pieces, a soldering device was prepared (see Fig. 3). In order to reduce the contact resistance between the RE-123 tapes and the copper end pieces 15 steps, each 0.08 mm deep and 20 mm long, were milled into the copper end pieces. The total width of the stepped ends is 60 mm, which is sufficient for 5 RE-123 stacks composed of 15 tapes of 12 mm width. Each of the 75 tapes will be held in position by means of a 5-stack clamping unit with 5 × 15 screws. The staggered ends of the RE-123 stacks are required to avoid that the current from outer tapes would have to cross the high resistance Hastelloy side of the inner tapes. In the central region of the HTS adapter the RE-123 stacks are bent. During the soldering process the RE-123 stacks were kept in position using a conforming die (see inset of Fig. 3).

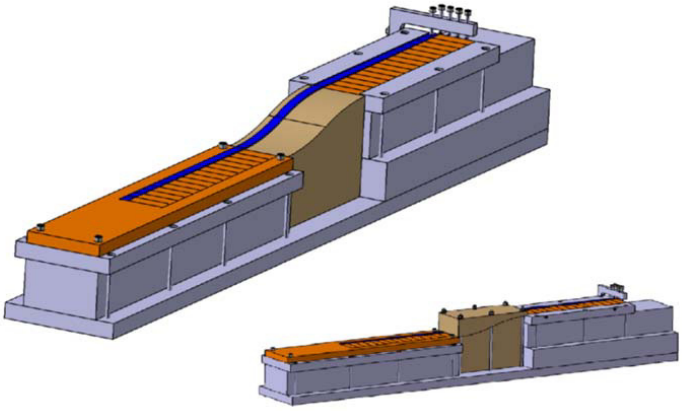

Fig. 3. 3D CAD model of the soldering device (left transformer side, right sample side).

After several soldering trials the RE-123 stacks were soldered to the copper end pieces of the HTS adapter with Pb-Sn solder in air. The temperature during soldering was controlled by thermocouples. To avoid damage of the RE-123 tapes a metal plate was inserted between the ends of the screws of the clamping unit and the superconducting tapes. Fig. 4 (left) shows the RE-123 stacks after soldering with Pb-Sn solder into the copper end piece with the clamping unit still present. Some excess solder pressed out of the RE-123 stacks is visible at the front edge of the clamping plate. Fig. 4 (right) shows the RE-123 stacks soldered into the copper end piece of the transformer side after removal of excess solder.

For a single stack of 15 RE-123 tapes, soldered to copper plates of 15 cm^2 cross-section with a contact area of 36 cm^2, a joint resistance of 108 nΩ was measured at 77 K. For comparison, the joint resistance of a 10 kA HTS current lead, made of 11 AgAuMg/Bi-2223 stacks (8 tapes per stack) is considered. The contact area at the warm end of the HTS module of this 10 kA current lead is 13.2 cm^2 and the cross-section of the copper piece connecting the HTS module with the heat exchanger part is ≈20 cm^2. For temperatures around 62 K, a joint resistance of 51 nΩ was measured by Wesche et al. [6]. Extrapolation of the data to 77 K provides a joint resistance of ≈70 nΩ. At 77 K the joint resistance is typically dominated by the contribution of copper. The performance of the soldered contact of the RE-123 stack and the copper plate is comparable to the warm end joint resistance of the 10 kA HTS current lead. For 5 RE-123 stacks in parallel, a joint resistance of around 22 nΩ would be expected at 77 K. In the present measurement, copper and superconductor are in parallel, whereas in the later joints two superconductors are in parallel separated only by a thin copper layer, which should lead to a much smaller joint resistance.

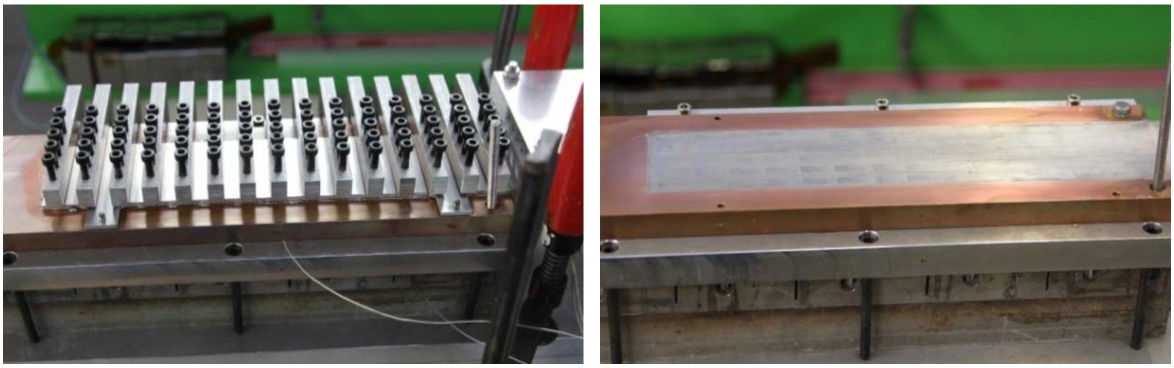

Fig. 4. Stacks of RE-123 coated conductors after soldering to the copper end piece on the transformer side with stacks still clamped in position (left) and after removal of the clamping unit and of excess solder (right).

Fig. 5. Assembled HTS adapter including the insulated stainless steel clamping plates (right) needed to press the two legs of the HTS Sultan sample to the contact area of the HTS adapter.

Fig. 5 shows the fully assembled HTS adapter with the two 500 mm long copper contacts of the transformer side (left) and the 300 mm long central copper contacts to be connected the HTS conductor under test (right). On the right the insulated stainless steel clamping plates are visible.

4. Design and manufacture of the heat exchanger

The design calculations for the tube-in-tube heat exchanger, required for the supply of intermediate temperature helium, were performed by M. Lewandowska [7] in collaboration with CRPP. The considered dimensions of the tube-in-tube heat exchanger are an inner diameter of the inner tube of 5 or 6 mm and an outer diameter of 7 or 8 mm. For the outer tube result inner and outer diameters of 9-10 mm and 11-12 mm, respectively. The refrigerator provides 4 to 10 g/s of cold helium with an inlet temperature of 4.5 K and an inlet pressure of 10 bar. The main requirement for the heat exchanger design is that the helium can be fed back to the cold gas return of the refrigerator. The cold gas return of the refrigerator can accept a maximum helium temperature of <20 K. A sketch of the studied cryogenic circuit is presented in Fig. 6. The cold helium gas supplied from the refrigerator is in counter flow with warm helium gas leaving the HTS sample. A heater before the inlet to the HTS conductor allows the adjustment of the helium temperature to the desired value. The temperature sensor TI is used to regulate the heater power. For measurements at temperatures close to 4.5 K, the cold helium can be returned via the bypass. The results of the design calculations indicate that a tube-in-tube heat exchanger of 5 to 6 m length with an inner copper tube and an outer stainless steel tube should limit the helium return temperature to around 18 K. A larger inner diameter of 6 mm of the inner copper tube is preferable because of the reduced pressure drop as compared to an inner diameter of 5 mm. The analysis of the cryogenic circuit by M. Lewandowska [7] identified that the option to have the warm helium in the inner tube is advantageous because of a reduction of the pressure drop in the circuit.

For the tube-in-tube heat exchanger manufactured at CRPP, a copper tube of 6 mm inner and 8 mm outer diameter has been selected. A stainless steel tube of 10 mm inner and 12 mm outer diameter has been used as outer tube. Due to space restrictions the length of the tube is only ~4 m. In order to increase length of the outer channel of the tube-in-tube heat exchanger (see Fig. 7) a pre-tinned copper wire, spirally wound with a twist pitch of 30 mm, has been soldered onto the inner copper tube.

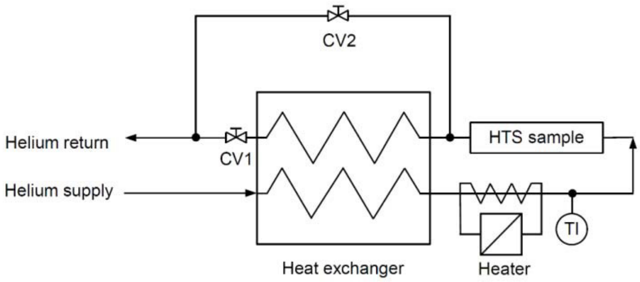

Fig. 6. Sketch of the studied cryogenic circuit. The refrigerator supplies 4-10 g/s helium of 4.5 K inlet temperature and an inlet pressure of 10 bar. The cold helium is in counter flow with the warm helium gas leaving the HTS sample. In case of 4.5 K tests the cold helium can be returned via the bypass (CV1 closed and CV2 opened) (adapted from M. Lewandowska [7]).

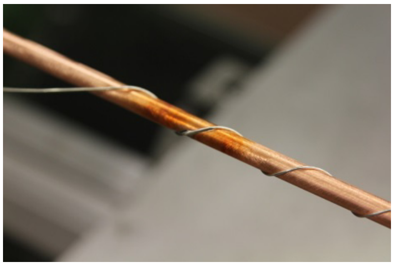

Fig. 7. Inner copper tube of the tube-in-tube heat exchanger. The inner and outer diameters of this copper tube are 6 and 8 mm. A pre-tinned copper wire of 1 mm diameter is spirally wound and soldered onto the inner copper tube with a twist pitch of 30 mm.

5. Commissioning of the HTS adapter

The commissioning of the HTS adapter and the heat exchanger is foreseen for the second half of 2014 in connection with the test of a 50 kA class HTS SULTAN sample manufactured at CRPP. In a second presentation at the ICEC 25 – ICMC 2014 (D. Uglietti et al. [4]), the manufacture of the HTS SULTAN sample is described.

6. Conclusion

An HTS adapter connecting the HTS SULTAN sample and the NbTi transformer at 4.5 K, which limits the heat flux between them to less than 10 W per leg, was manufactured at CRPP. In each of the two legs of the HTS adapter, the current is carried by 75 RE-123 tapes of 12 mm width. The tapes are arranged in 5 stacks, each composed of 15 RE-123 tapes with staggered ends. The expected critical current reaches 100 kA at 40 K. Using a dedicated soldering device the HTS stacks were soldered with Pb-Sn solder to the copper end plates followed by the assembly with the insulators and stainless steel parts. For the supply of intermediate temperature helium (20-50 K), a tube-in-tube heat exchanger was manufactured at CRPP. Due to the counter flow of 4.5 K helium supplied by the refrigerator and the warm helium leaving the HTS sample under test the helium can be returned to the refrigerator as cold gas with a temperature of less than 20 K.

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